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Fermi acceleration in astrophysical jets

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Abstract We consider the acceleration of energetic particles by Fermi processes (i.e., diffusive shock acceleration, second order Fermi acceleration, and gradual shear acceleration) in relativistic astrophysical jets, with particular attention given to recent progress in the field of viscous shear acceleration. We analyze the associated acceleration timescales and the resulting particle distributions, and discuss the relevance of these processes for the acceleration of charged particles in the jets of AGN, GRBs and microquasars, showing that multi-component powerlaw-type particle distributions are likely to occur.

Keywords Particle acceleration, jets, Microquasars, Active Galaxies, Gamma-Ray bursts

1 Introduction

Ever since the earliest detections of non-thermal emission from jet-type astrophysical sources astrophysicists have conjectured upon its origin. Today, it is widely believed that Fermi processes, where particle acceleration occurs as a consequence of multiple scattering of energetic particles off magnetic turbulence with a small energy change in each event, are responsible for the production of the non-thermal powerlaw particle distributions as required by the observed synchrotron and inverse Compton emission properties of these jets. First-order Fermi acceleration at strong nonrelativistic shocks, observationally well established to take place in the shells of supernova remnants (e.g., Aharonian et al., 2004), can, for example, naturally account for the commonly required powerlaw particle spectra $N(\gamma) \propto \gamma^{-s}$ with spectral indices $s \simeq 2$ and is also a sufficiently fast and efficient mechanism. On observational grounds such an interpretation is strongly supported by (i) the fact that the knotty features detected in extragalactic jets can be directly identified with sites of strong shock formation, and (ii) by the multiple detection of characteristic variability patterns (e.g., spectral index hysteresis) associated with efficient first-order Fermi acceleration in AGN-type jets (Kirk et al., 1998). Recent high-resolution studies of extragalactic jets, however, indicate that first-order Fermi acceleration alone, localized by its very nature, cannot satisfactorily account for the detection of extended high-energy emission. In the case of the quasar 3C 273, for example, the optical spectral index is found to vary only smoothly along the (large-scale) jet with no signs of strong synchrotron cooling at any location in the jet, e.g., between knots, contrary to expectations from shock acceleration scenarios (Jester et al., 2001; Jester et al., 2005), thus suggesting the need of a continuous stochastic re-acceleration mechanism operating all along the jet. Shear and/or second-order Fermi particle acceleration, although possibly swamped by first-order Fermi processes in the vicinity of a flow discontinuity, appear to be the most natural candidates that may account for these observations.
Here we analyse some of the essential properties of Fermi particle acceleration processes and discuss their relevance for different astrophysical jet sources. We wish to note that we are focusing on mechanisms operating *within* a jet and not at its working surface (hot spot).

2 Fermi acceleration processes

Fermi particle acceleration (Fermi, 1949) is essentially based on the fact the energetic particles (velocity $v \sim c$) can gain energy by elastically scattering off magnetic turbulence structures or irregularities moving with some

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characteristic velocity $\mathbf{u}$. Following a simple microscopic treatment and assuming energy to be conserved in the comoving scattering frame, the energy change of a particle due to collision is simply given by

$$\Delta\epsilon := \epsilon_2 - \epsilon_1 = 2\Gamma^2(\epsilon_1 u^2/c^2 - \mathbf{p}_1 \cdot \mathbf{u}) \,, \tag{1}$$

where $\Gamma = (1 - u^2/c^2)^{-1/2}$ is the Lorentz factor, $\mathbf{p} = E\mathbf{v}/c^2$ the particle momentum and the indices 1 and 2 denote particle properties before and after scattering. A particle thus gains or loses energy depending on whether it suffers head-on/approaching ($\mathbf{p_1} \cdot \mathbf{u} < 1$) or following/overtaking ($\mathbf{p_1} \cdot \mathbf{u} > 1$) collisions. Based on these considerations the following cases may be distinguished:

2.1 Shock or first-order Fermi acceleration

Suppose that a strong (nonrelativistic) shock wave propagates through the plasma. Then in the frame of the shock the conservation relations imply that the upstream velocity (ahead of the shock) is much higher than the downstream velocity (behind the shock), i.e., $u_u/u_d = (\gamma_h + 1)/(\gamma_h - 1)$, with $\gamma_h > 1$ denoting the ratio of specific heats, so that the two regions may be regarded as two converging flows. Hence, in the upstream [downstream] rest frame the plasma from the other side of the shock (downstream [upstream]) is always approaching with velocity $u = u_u - u_d$, so that to first order there are only head-on collisions for particles crossing the shock front. The acceleration process, although stochastic, thus always leads to a gain in energy, so that for magnetic turbulence structures virtually comoving with the plasma flow, the energy gain [eq. (1)] becomes first order in u/c, i.e.,

$$\frac{\Delta\epsilon}{\epsilon_1} \propto \frac{u}{c} \,. \tag{2}$$

The acceleration timescale $t_{\rm acc}$ for diffusive shock acceleration depends on both, the upstream and downstream residence times (Drury, 1983). In general, for a useful order of magnitude estimate $t_{\rm acc} \sim 3\kappa/u_s^2$ (Kirk and Dendy, 2001), with u_s the shock speed measured in the upstream frame and κ the spatial diffusion coefficient. Particularly, for quasi-parallel shocks with $\kappa = \kappa_d \simeq \kappa_u$ one finds $t_{\rm acc} \simeq 20\,\kappa/u_s^2$ (e.g., Protheroe and Clay, 2004), so that in the quasi-linear limit $|\delta B| \stackrel{<}{\sim} B$, where $\kappa \stackrel{<}{\sim} \kappa_B \simeq r_g\, c/3$,

$$t_{\rm acc} \stackrel{>}{\sim} 6 \frac{\gamma\, m\, c}{e\, B} \left(\frac{c}{u_s}\right)^2 \,. \tag{3}$$

In theory, much faster acceleration may be achieved for quasi-perpendicular shocks, where – assuming quasi-linear approximation ($|\delta B| \ll B$) to hold – the (perpendicular) diffusion coefficient κ can be significantly smaller than the above quoted Bohm limit (Jokipii, 1987). However, for realistic astrophysical applications such a situation seems at least questionable given recent numerical results which show that cosmic ray streaming at a shock front can lead to strong self-generated turbulence beyond the quasi-linear regime (Lucek and Bell, 2000).

Fermi acceleration at (unmodified) nonrelativistic shocks is known to produce powerlaw particle spectra $N(\gamma) \propto \gamma^{-s}$, which are essentially independent of the microphysics involved and only dependent on the shock compression ratio $\rho = u_u/u_d$ (where $1 < \rho \leq 4$), i.e.,

$$s = \frac{(\rho + 2)}{(\rho - 1)} \,, \tag{4}$$

so that for strong shocks ($\rho = 4$ in the test particle limit) the famous $s = 2$ result is obtained (Drury, 1983; Blandford and Eichler, 1987). Note that incorporation of non-linear effects (e.g., strong shock modification) usually suggests values $s < 2$ at high energies (Berezhko and Ellison, 1999). On the other hand, incorporation of anomalous (non-diffusive) transport properties associated with the wandering of magnetic field lines, may efficiently reduce cross-field propagation and thus allow values up to $s = 2.5$ (Kirk et al., 1996).

To undergo efficient first-order Fermi acceleration at nonrelativistic shocks electrons already have to be preaccelerated up to seed Lorentz factors $\gamma_e > m_p/m_e\,(V_A/c)$ (ion cyclotron resonance condition). Recent simulations suggest that this "problem of injection" may possibly be resolved by electrostatic wave (ESW) surfing – when ESWs, excited by streaming ion beams, saturate by trapping electrons, thus transporting them across the magnetic field – and/or acceleration due to ESW collapse (McClements et al., 2001; Dieckmann et al., 2004).

2.2 Second-order Fermi acceleration

Suppose that the scattering centres have a non-negligible random velocity component. In the absence of dominant shock effects (see above), energetic particles will thus experience both head-on and overtaking collisions, i.e., lose and gain energy. However, as the rate of collisions is proportional to $|\mathbf{v_1} - \mathbf{u}|/v_1 \simeq (1 - \mathbf{v}_1\mathbf{u}/v_1^2)$, there is a higher probability for head-on compared to overtaking collisions, which gives an average energy gain per collision that is second order in u/c, i.e.,

$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 \tag{5}$$

when averaged over all momentum directions. Second-order Fermi acceleration thus represents a classical example of a stochastic acceleration process due to many small, nonsystematic energy changes. As such it can be described by a diffusion equation in momentum space (Skilling, 1975; Melrose, 1980), i.e., the isotropic phase space distribution (averaged over all momentum directions) evolves according to

$$\frac{\partial f(p)}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p(p) \frac{\partial f(p)}{\partial p}\right) \,, \tag{6}$$

with $D_p(p) \propto < (\Delta p)^2 >$ the diffusion coefficient in momentum space. A statistical treatment taking the small anisotropy of the particle distribution in the laboratory frame into account allows proper calculation of the Fokker-Planck coefficients (Duffy and Blundell, 2005) and for $v \sim c$ gives $D_p = (u/c)^2 p^2/(3\tau) \propto p^2/\tau$, where $\tau \simeq 1/(n\,\sigma\,c)$ is a mean scattering time and n is the number density of scatterers. For the scattering off forward and reverse propagating Alfven waves a similar expression can be derived (Skilling, 1975; Melrose, 1980; Webb, 1983), i.e.,

$$D_p \simeq \frac{p^2}{3\tau}\left(\frac{V_A}{c}\right)^2 , \tag{7}$$

where $V_A = B/\sqrt{4\pi\rho}$ is the Alfven velocity. This implies a characteristic acceleration timescale

$$t_{\rm acc} = p^3\left[\frac{\partial}{\partial p}\left(p^2 D_p\right)\right]^{-1} = \frac{3}{(4-\alpha)}\left(\frac{c}{V_A}\right)^2 \tau \tag{8}$$

for $\tau = \lambda/c \propto p^\alpha$. Comparison with the results for diffusive shock acceleration shows that second-order Fermi acceleration is typically a factor of order $(u_s/V_A)^2$ slower than first-order Fermi acceleration.
Second-order Fermi acceleration is usually expected to lead to particle spectra $N(\gamma) \propto \gamma^{-s}$ that are typically flatter than those produced by standard strong shock acceleration, i.e., $s < 2$ (cf. also Virtanen and Vainio, 2005). For example, adding both a monoenergetic source term $Q\,\delta(p-p_0)$ and a particle loss term $-f/T$ on the rhs of eq. (6), assuming $\alpha = 0$ and steady state, one finds

$$s = \frac{3}{2}\sqrt{1 + 16\,t_{\rm acc}/(9\,T)} - \frac{1}{2} \tag{9}$$

above p_0, so that for $T \gg t_{\rm acc}$ for example, one has $N(\gamma) \propto \gamma^{-1}$.

2.3 Gradual shear acceleration

Consider now the case where the magnetic turbulence structures are embedded in a gradual shear flow $\mathbf{u} = u_z(x)\mathbf{e}_z$, assuming their random velocities to be small compared to the characteristic shear velocity. Particles traveling across the shear thus encounter scattering centres with different (although non-random) local velocities $u_z(x)$. Similar to the case of 2nd order Fermi acceleration, the average energy gain per collision becomes second order in $\tilde{u}/c$, where $\tilde{u} = (\partial u_z/\partial x)\lambda$ denotes the characteristic relative velocity of the scattering centres, $\lambda \simeq c\tau$ is the particle mean free path and τ is the mean scattering time, i.e., one finds (cf. also Jokipii and Morfill, 1990)

$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{\partial u_z}{\partial x}\right)^2 \tau^2 . \tag{10}$$

Again, as a stochastic process shear acceleration can be described by a diffusion equation in momentum space, i.e., an equation of type eq. (6). For nonrelativistic gradual shear flows a proper statistical treatment (Rieger and Duffy, 2006) gives

$$D_p = \tilde{\Gamma} p^2 \tau \propto p^2 \tau , \tag{11}$$

where $\tilde{\Gamma} = (\partial u_z/\partial x)^2/15$ is the shear flow coefficient and $\tau = \tau_0\,p^\alpha$ is the mean scattering time. This implies a characteristic acceleration timescale [cf. eq. (8)]

$$t_{\rm acc} = 1/([4+\alpha]\,\tilde{\Gamma}\,\tau) \tag{12}$$

which, in contrast to first- and second-order Fermi, is inversely proportional to the particle mean free path $\lambda \simeq \tau/c$. Eq. (12) can be generalized to the relativistic case by replacing $\tilde{\Gamma}$ by its relativistic counterpart (Rieger and Duffy, 2004, eq.(3)). In particular, for a (cylindrically collimated) shear flow decreasing linearly with radial coordinate from relativistic to nonrelativistic speeds over a distance $\Delta r = (r_2 - r_1)$, the maximum acceleration timescale is of order

$$t_{\rm acc} \simeq \frac{3(\Delta r)^2}{\gamma_b(r_1)^4 \lambda\, c} \tag{13}$$

where $\gamma_b(r)$ is the local bulk Lorentz factor of the flow. In the simplest case, assuming quasi steady state conditions and monoenergetic injection, the functional form of the local particle distribution $N(p) \propto p^2\,f(p)$ becomes

$$N(p) \propto p^{-(1+\alpha)} \tag{14}$$

above p_0 for $\alpha > 0$ (Berezhko and Krymskii, 1981; Rieger and Duffy, 2006). From an astrophysical point of view, acceleration becomes essentially non-gradual when the particle mean free path becomes larger than the width of the transition layer. In this case results from the study of relativistic non-gradual shear flows (e.g., Ostrowski, 1990) can be employed to analyse issues of maximum energies and resulting particle distributions.

3 Application to astrophysical jet sources

Apart from lateral particle escape and limited jet activity, radiative synchrotron losses represent one of the most servere constraints for the acceleration of energetic particle in astrophysical jets. We may estimate the maximum achievable particle energy in the presence of synchrotron losses by equating the isotropic synchrotron cooling timescale $t_{\rm cool} = (9\,m^3\,c^5)/(4\,\gamma\,e^4\,B^2)$ with the corresponding acceleration timescale. For non-relativistic shock acceleration this results in a maximum comoving Lorentz factor (provided $r_g(\gamma_{\rm max})$ is still smaller than the width of the jet) of order

$$\gamma_{\rm max}^{1st} \simeq 9 \cdot 10^9 \left(\frac{1\,\rm G}{B}\right)^{1/2}\left(\frac{m}{m_p}\right)\left(\frac{u_s}{0.1\,\rm c}\right) \tag{15}$$

with m_p the proton mass, whereas in the case of second order Fermi with $\lambda \simeq r_g$ one finds

$$\gamma_{\rm max}^{2nd} \simeq 2 \cdot 10^8 \left(\frac{1\,\rm G}{B}\right)^{1/2}\left(\frac{m}{m_p}\right)\left(\frac{V_A}{0.001\,\rm c}\right) . \tag{16}$$

For $\lambda \sim r_g$ the acceleration timescale in a gradual shear flow [e.g., eq. (13)] scales with γ in the same way as the cooling timescale, so that radiative losses are no longer able to stop the acceleration process once it has started to operate efficiently. For a linearly decreasing flow profile efficient acceleration thus becomes possible if the shear is sufficiently strong, i.e., provided the relation

$$\Delta r \lesssim 0.1\,\gamma_b(r_1)^2 \left(\frac{m}{m_p}\right)^2 \left(\frac{1\,\mathrm{G}}{B}\right)^{3/2} \;\; \mathrm{pc} \qquad (17)$$

holds. These considerations suggest the following:

3.1 Relativistic AGN jets

In the case of relativistic AGN jets, diffusive shock acceleration (*first order Fermi*) processes represent the most efficient and plausible mechanism for the origin of the observationally required non-thermal powerlaw distributions in their inner (sub-parsec scale) jets. For characteristic parameters, e.g., $u_s \sim 0.1$ c, $B \sim 0.1\,b_0$ Gauss, maximum electron Lorentz factors $\gamma_{\max} \lesssim 10^7\,b_0^{-1/2}$ [cf. eq. (15)] may be reached suggesting that for blazar-type sources with $\gamma_b \sim 10$ an electron synchrotron contribution up to $\nu_{\rm obs} \sim 10^5 \gamma_b\,\gamma_{\max}^2\,b_0 < 2 \cdot 10^{20}$ Hz, i.e., well in the hard X-ray regime, may be possible, provided IC losses do not dominate. Furthermore, the variability in the high energy regime may be very fast if associated either with $t_{\rm acc}$ or $t_{\rm cool}$. One expects a similar expression for the acceleration timescale [eq. (3)] to hold if shocks in blazar-type jets are mildly relativistic ($u_s \gtrsim 0.3$ c), although the spectral index may then be somewhat steeper, i.e, $s > 2$, and the explicit results more dependent on the exact scattering conditions (e.g., Lemoine and Pelletier, 2003).
As noted in the introduction (e.g., see the case of the famous quasar 3C 273), the situation is somewhat different with respect to the (collimated) relativistic large-scale jets in AGNs, [1] where observational evidence suggests that shock acceleration is not sufficient to account for the observed smooth evolution of the spectral index. Stochastic acceleration like shear or second-order Fermi processes may represent the most natural candidates for distributed acceleration mechanisms operating all along the jet (Stawarz and Ostrowski, 2000; Rieger and Duffy, 2004). For a quasi-uniform flow profile with $\gamma_b \sim (3-5)$ and a characteristic set of parameters, $B \sim 10^{-5} b_0$ G, $b_0 \gtrsim 1$ (e.g., Stawarz, 2005) and $V_A \sim 10^8\,b_0$ cm/s, *second-order Fermi* acceleration [eq. (16)] may account for electrons with maximum Lorentz factor up to $\gamma_{\max} \sim 10^8\,b_0^{1/2}$, corresponding to synchrotron emission up to $\nu_{\rm obs} \sim 5 \cdot 10^{17}\,b_0^2\,\mathrm{Hz} \lesssim 2\,b_0^2$ keV. Neglecting inverse Compton losses for a moment, it seems possible that synchrotron emission from electrons accelerated via second-order Fermi processes can, at least in principle, account for the observed extended emission in the optical (Jester et al., 2001), and perhaps even in the Chandra X-ray regime (cf. Harris and Krawczynski, 2006). If this is indeed the case, the radiating electron distribution $N(\gamma) \propto \gamma^{-s}$ is likely to consist of at least two components: One, localized at the observed knots and corresponding to strong shock acceleration with spectral index $s \simeq 2$, and one, distributed in between knots and associated with second order Fermi processes and flatter spectral index $s < 2$. It is likely, however, that the real situation is much more complex. There is strong evidence, for example, that in reality astrophysical jets do not possess a simple uniform flow profile as often used for spectral modelling. In particular, the density and velocity gradients associated with extreme astrophysical environments are likely to result in a non-negligible velocity shear across the jet. In the case of AGN such shear flows are indeed observationally well-established, e.g., see Laing & Bridle (2002) and Laing et al. (2006) for recent observational results and modelling, and Rieger & Duffy (2004) for a recent review of the phenomenological evidence. For the characteristic parameters specified above, eq. (17) then suggests that on kiloparsec scales efficient *shear acceleration* of electrons may be possible provided the velocity decreases significantly on radial scales $\Delta r_e \lesssim$ several percent of the total jet width $r_j \sim 1$ kpc. Essentially no such constraint applies to protons (i.e., $\Delta r_p \sim r_j$, cf. eq. [17]), so that compared to the case of electrons efficient proton acceleration should be much more common. These considerations have interesting observational consequences: (i) Suppose that the velocity shear in the large-scale jet is sufficiently strong (e.g., significant velocity decay over $\Delta r_e \sim$ several percent of r_j) to allow for efficient electron acceleration, the required high energy seed particles ($\gamma \gtrsim 10^6\,b_0$) being provided by first and second-order Fermi processes. Even for the simplistic case of V_A independent of r, shear acceleration will then begin to dominate over second-order Fermi processes for electrons with $\gamma \gtrsim 10^8\,(\Delta r/10\,\mathrm{pc})\,(V_A/0.01\,c)\,b_0$, resulting in a third radiating electron component with local index $s \simeq 2$. If this is indeed the case, the observed spectral index in the optical-UV (probably due to second-order Fermi acceleration) may well be different from the one measured in the X-ray regime (likely due to shear acceleration). (ii) On the other hand, even if the large-scale shear is very weak (e.g., say $\Delta r \sim 0.3$ kpc) efficient acceleration of protons remains still possible suggesting that relativistic gradual shear flows may allow acceleration of protons up to ultra-high energies of $10^{18} - 10^{19}$ eV (where $\lambda \sim \Delta r$), i.e., well up to the "angle" of the cosmic ray energy spectrum at around 3×10^{18} eV. Subsequent non-gradual shear acceleration may then reach even higher proton energies, per-

[1] There is now mounting observational evidence that the jets of powerful FR II type sources are still relativistic ($\gamma_b \sim 5$) on large kpc scales (e.g., Sambruna et al., 2001; Tavecchio et al., 2000).

haps even up to $\sim 10^{20}$ eV (Ostrowski, 1990 and 1998). If so, then one would naturally expect a change in spectral index around the angle when gradual shear is replaced by non-gradual shear acceleration usually associated with flatter particle spectra.

3.2 Ultrarelativistic GRB outflows

While there is strong evidence today that GRBs are associated with collimated ultra-relativistic outflows or jets (Rhoads, 1999; Kulkarni et al., 1999; Greiner et al., 2003), it is still a matter of ongoing debate whether these jets exhibit a rather uniform ("top-hat") or a more universal structured ("power-law" or "Gaussian"-type) hydrodynamical profile (e.g., Rhoads, 1999; Rossi et al., 2002). In any case, it is commonly believed that shock accelerated electrons are, via synchrotron radiation processes, responsible for both, the prompt gamma-ray burst and its afterglow emission (Piran, 2005): Efficient electron acceleration at mildly relativistic internal shocks (Γ_s of a few) arising from velocity variations in the relativistic outflow, is usually thought to be behind the powerful burst of γ-rays (Rees and Mészáros, 1994), while electron acceleration at a decelerating, highly relativistic ($\Gamma_s \gg 1$) external shock is believed to be responsible for the afterglow emission, peaking successively in the γ-rays, X-rays, optical and the radio regime (Rees and Mészáros, 1992). Whereas to order of magnitude accuracy, the acceleration timescale at a mildly relativistic shock front may be reasonably approximated by the Larmor time, i.e., $t_{\rm acc} \sim r_g/c$, the acceleration timescale at highly relativistic shocks may be as short as a fraction $1/\Gamma_s$ of the (upstream) Larmor time (e.g., Gallant and Achterberg, 1999; Lemoine and Pelletier, 2003). The latter result is related to the fact that (for all but the initial crossing) particles upstream cannot be deflected beyond an angle $\sim 1/\Gamma_s$ before being overtaken by the shock. Accordingly, particles can also only gain a factor of order Γ_s^2 in energy in the first shock crossing cycle, whereas the energy gain is reduced to a factor of order 2 for subsequent crossing events as particles upstream do not have sufficient time to isotropise (Gallant and Achterberg, 1999; Achterberg et al., 2001; cf. however also Derishev et al., 2003). In general the power-law spectral index of the accelerated particle distribution for ultra-relativistic shock acceleration is strongly dependent on the exact scattering conditions. In the case of pitch-angle diffusion the simulations give $s \sim 2.2 - 2.3$ (e.g., Bednarz and Ostowski, 1998; Kirk and Duffy, 1999; Achterberg et al., 2001; Baring, 2005).

It has been suggested by Waxman, that the first- (Waxman, 2004) and perhaps also second-order (Waxman, 1995) Fermi processes, known to accelerate electrons in GRB outflows with $\gamma_b \sim 300$ to gamma-radiating energies, may also allow an efficient acceleration of protons to ultra-high cosmic ray energies in excess of 10^{20} eV.

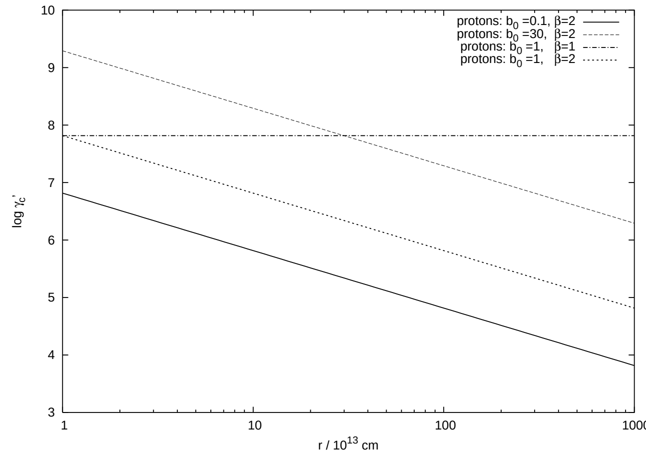

Fig. 1 Plot of the critical (comoving) Lorentz factor γ_c' as a function of distance r assuming an internal shock speed of $\beta_s = 0.95$ c. Above γ_c' the shear acceleration timescale becomes smaller than the shock acceleration timescale, so that proton acceleration by shear becomes more efficient.

While this seems in principle possible, the analysis of the natural shear acceleration potential in expanding ultra-relativistic GRB flows (Rieger and Duffy, 2005) suggests that under a reasonable range of conditions shear acceleration may be more relevant for the production of UHE cosmic rays than shock-type acceleration processes. This is illustrated in Fig. 1, where we have plotted the critical (comoving) proton Lorentz factor γ_c', defined by $t_{\rm acc}(\text{shear}) = \text{t}_{\rm acc}(\text{shock})$, as a function of distance r, assuming an intrinsic magnetic field strength $B = 1000\, b_0\, (10^{13}\,\text{cm}/r)^\beta$ and $\eta\,\xi \simeq 1$ (cf. Rieger and Duffy, 2005, for more details), noting that in order to achieve UHE greater than 10^{20} eV, characteristic (comoving) proton Lorentz factors of $\gtrsim 4 \cdot 10^8$ are required

3.3 Mildly relativistic Microquasar jets

Similar to the case of extragalactic AGN jets, Fermi-type processes are likely to lead to efficient particle acceleration in the scale down versions of AGNs known as galactic Microquasars (MQs) (Mirabel and Rodríguez, 1999). MQs are (radio-loud) X-ray binary systems where a compact object (a neutron star or stellar mass black hole) accretes matter from a normal star in orbital motion around it and (at least in the low-hard state) produces a (quasi-stable) collimated, mildly relativistic jet with characteristic bulk velocities in the range of $0.2 - 0.9$ c (cf. Gallo et al., 2003) and observed jet lengths in some sources well in excess of several hundred AUs. The detection of extended, nonthermal radio emission in MQs substantiate the presence of relativistic electrons in their jets. Indeed, detailed modelling reveals that synchrotron emission from relativistic electrons is likely to be important in the radio up to the soft gamma-ray regime for a magnetic field close to equipartition (Bosch-

Ramon et al., 2006). Assuming a magnetic field scaling $B(z) = 10^5\, b_0\, (z_0/z)$ G, with $b_0 \sim 1$ and $z_0 \sim 50\, R_g$ (e.g., Bosch-Ramon et al., 2006), synchrotron-limited, non-relativistic shock processes ($u_s \sim 0.1\,$c) give electron Lorentz factors $\gamma_e \lesssim 1.5 \cdot 10^4\, b_0^{-1/2}\, (z/z_0)^{1/2}$, cf. eq (15), thus allowing for electron synchrotron emission up to $\nu_{\rm obs} \sim 2 \cdot 10^{19}$ Hz ($\sim 10^5$ eV), whereas the condition of lateral confinement limits possible maximum Lorentz factors for protons (electrons) to $\gamma_p \lesssim 7 \cdot 10^4\, b_0$ ($\gamma_e \lesssim 10^8\, b_0$), assuming a typical half-opening angle $\phi \simeq 0.05$ rad. Shock acceleration alone seems thus not to be able to provide the required high-energy electrons suggested by spectral modelling results, e.g., see the required high acceleration efficiency in the case of LS 5039 (Parades et al. 2006). Interestingly, however, post-acceleration of electrons, occurring on scales larger than $z/z_0 \sim 10$ [cf. eq. (17)] within a strong ($\Delta r_e \sim$ several percent of r_j) velocity shear may provide a possible solution by boosting shock-accelerated electrons further up to maximum Lorentz factors $\gamma_e \sim 10^6$, substantiating the notion that SSC (Klein-Nishina) or star IC (Thomson) may yield VHE γ-rays possibly reaching several TeV energies (Paredes et al., 2000). We note that further evidence for particle acceleration beyond standard first-order Fermi has been suggested recently (Gupta and Böttcher, 2006).

4 Conclusions

While the relations derived above essentially rely on a simple test particle approach, thereby neglecting any back-reaction effects of the accelerated particles (e.g., strong shock modification, viscous kinetic energy dissipation or significant wave damping), we believe that they still allow reasonable order of magnitude estimates for many cases of interest. Hence, although there are different physical conditions in the relativistic jets of AGNs, Microquasars and GRBs, our analysis suggests that Fermi acceleration processes offer a powerful and attractive explanatory framework for the origin of the non-thermal particle distributions required within these sources. In particular, due to its inverse scaling, $t_{\rm acc} \propto 1/\lambda$, shear acceleration is likely to become important at high energies and may thus naturally lead to the presence of an at least two-component energetic particle distribution.

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